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Machine learning for Linac RF Optimization

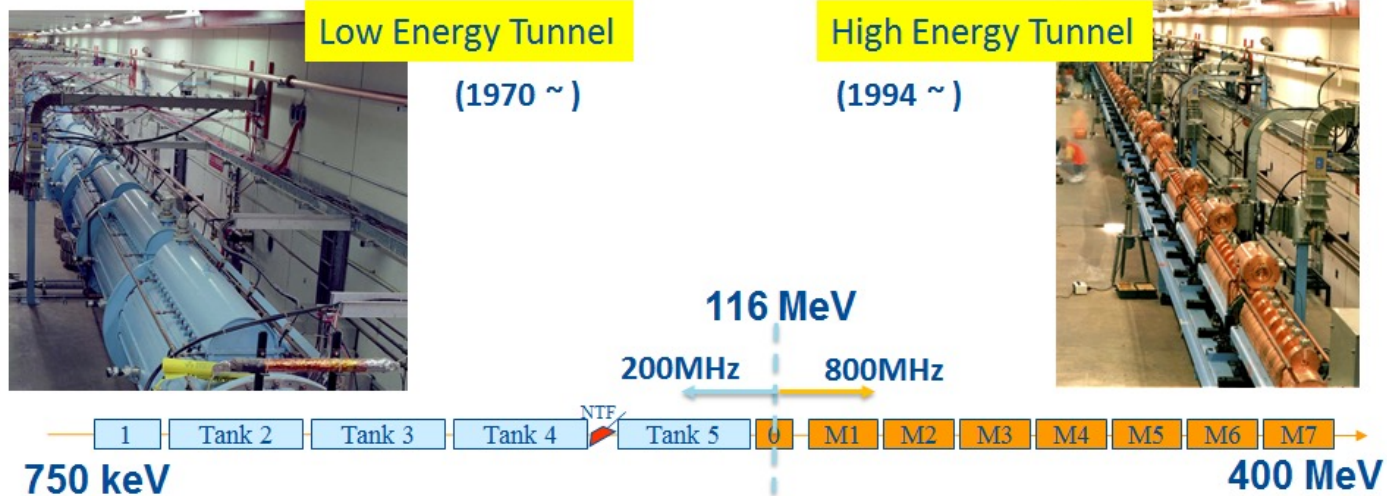R. Sharankova, K. Seiya, M. Wesley, M. Mwaniki

AI for Accelerators WS

14 Jan 2022

Contents

- Fermilab Linac: brief overview

- Longitudinal optimization

- Linac diagnostics

- Machine learning methods for RF optimization

  - Goals

  - Status

- Summary and outlook

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Low Energy Tunnel (1970 ~) High Energy Tunnel (1994 ~)

116 MeV

200MHz   800MHz

NTF

| 1 | Tank 2 | Tank 3 | Tank 4 | Tank 5 | 0 | M1 | M2 | M3 | M4 | M5 | M6 | M7 |

750 keV   400 MeV

- Drift tube Linac: 5 tanks
  - Resonant RF frequency 201 MHz
- Side-coupled Linac: 7 modules
  - Resonant RF frequency 805 MHz
- Transition section: Buncher & Vernier
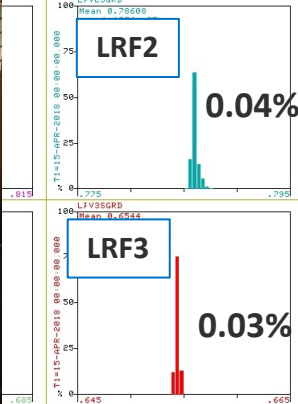 - Match beam structure b/n DTL & SCL

Status
Linac output: 25mA
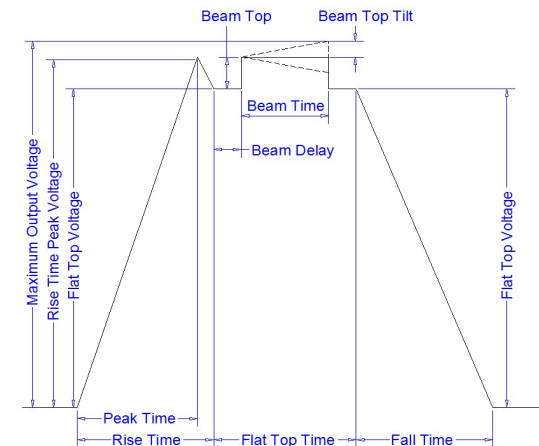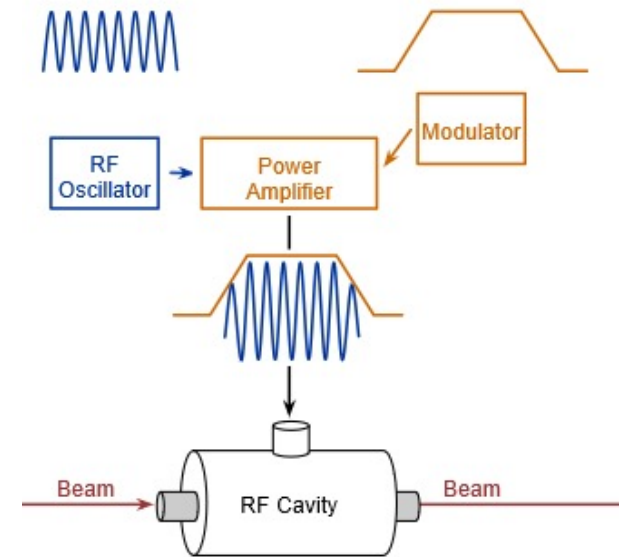Pulse length: 35 μsec
Efficiency: 94%

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Linac RF systems

DTL RF system components

Gradient stability

LRF2   **0.04%**

LRF3   **0.03%**
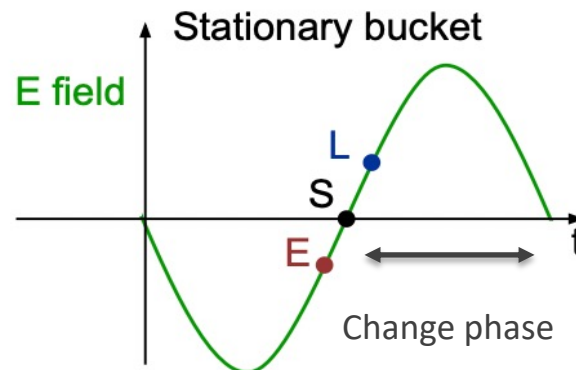

- Linac RF systems main components
  - Low power, high-freq pulse (Driver)
  - High power, low frequency pulse (Modulator)
  - Combined by Power Amplifier/Klystron
  - Sent to cavity via transmission line

Schematic taken from Operations Department Concepts Rookie Book: https://operations.fnal.gov/rookie_books/concepts.pdf

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Longitudinal optimization

- To reduce beam losses and increase beam throughput, want to minimize beam emittance
  - Longitudinal focusing: RF phase set point and gradient
- RF parameters
  - cavity phase: determines the timing of the RF field w.r.t. incoming beam
  - Gradient: determines the amplitude of acceleration
 - 17 cavities x(phase, gradient)= 34 tunable RF params

Stationary bucket

E field

L

S

E

t

Change phase

Schematic taken from Operations Department Concepts Rookie Book: https://operations.fnal.gov/rookie_books/concepts.pdf

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Longitudinal Optimization in Linac Operations

- Losses and beam currents drift daily
  - Ambient temps & humidity changes affect resonant frequencies
  - Source instabilities
- Daily tuning of RF params for min losses & max beam output
  - RFQ, Buncher, DTL Tank 5 phase adjustments
- Challenges
  - Drift effects hard to predict/simulate: rely on instrumentation
  - Human operator cannot simultaneously optimize multiple parameters
- Our approach:
  - Revisit Linac diagnostics to ensure robust & ample data
  - Develop machine learning (ML) methods for multi-dimensional optimization & automation of RF tuning
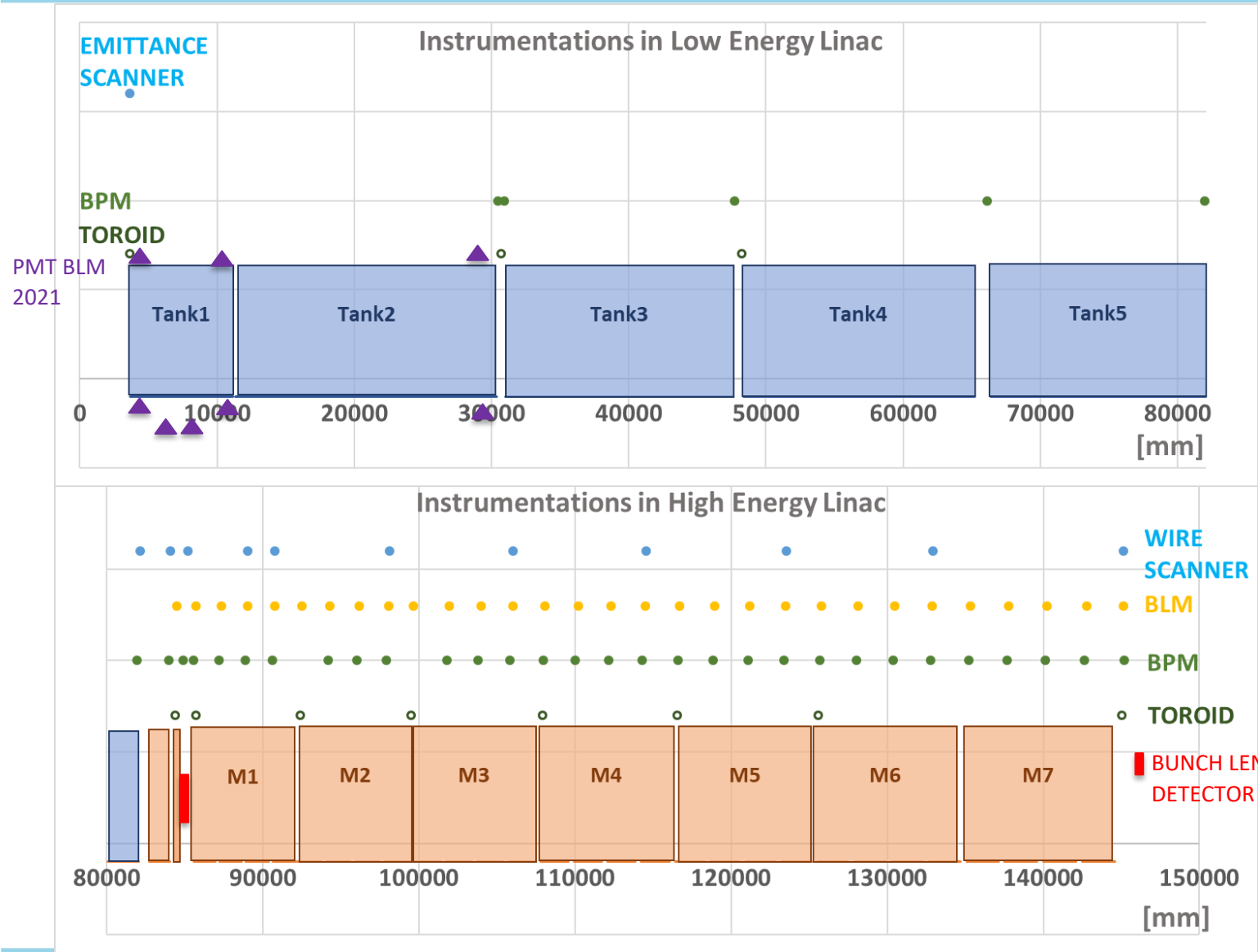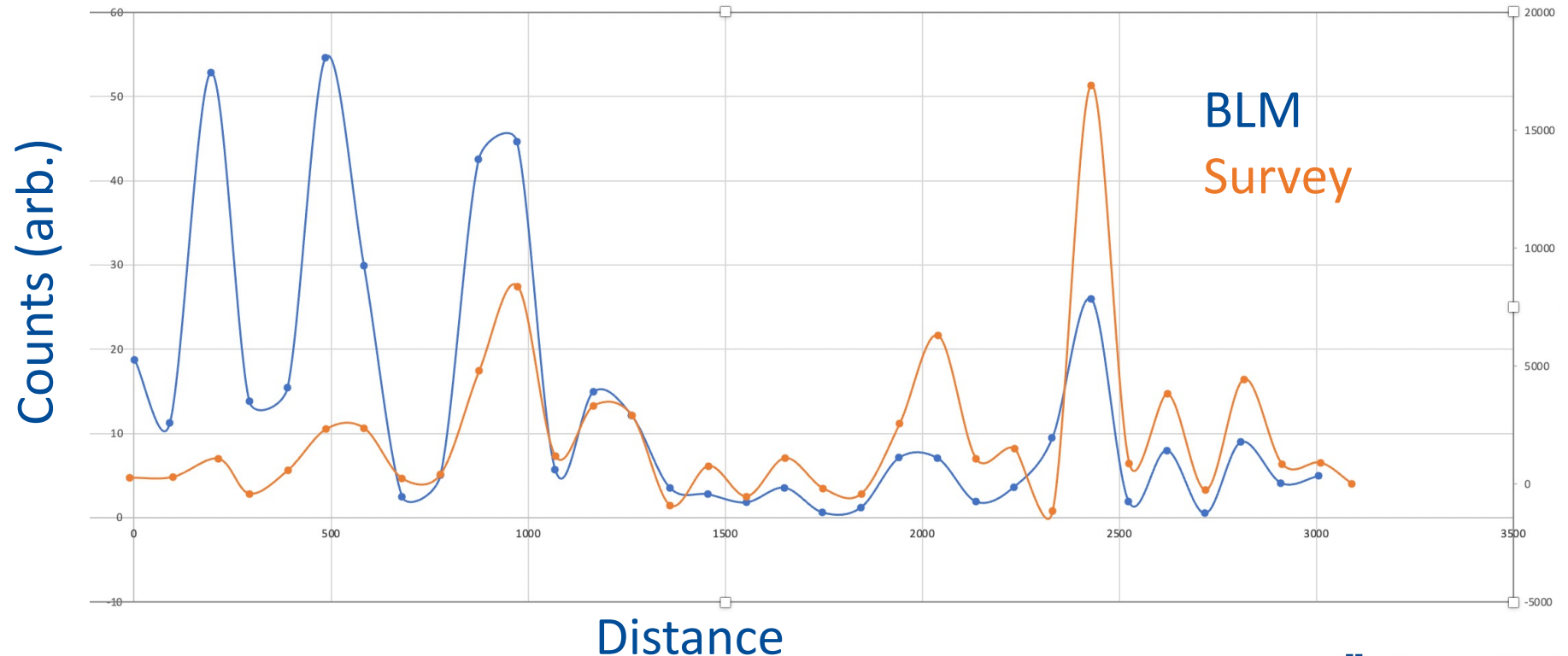
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Instrumentation in Linac

Instrumentation in Linac

- Status as of Jan 2021
  - DTL diagnostics limited by tank design
    - No BLMs in original design, only chipmunks in tunnel
  - Multiple BLM, TOR and BPM in SCL
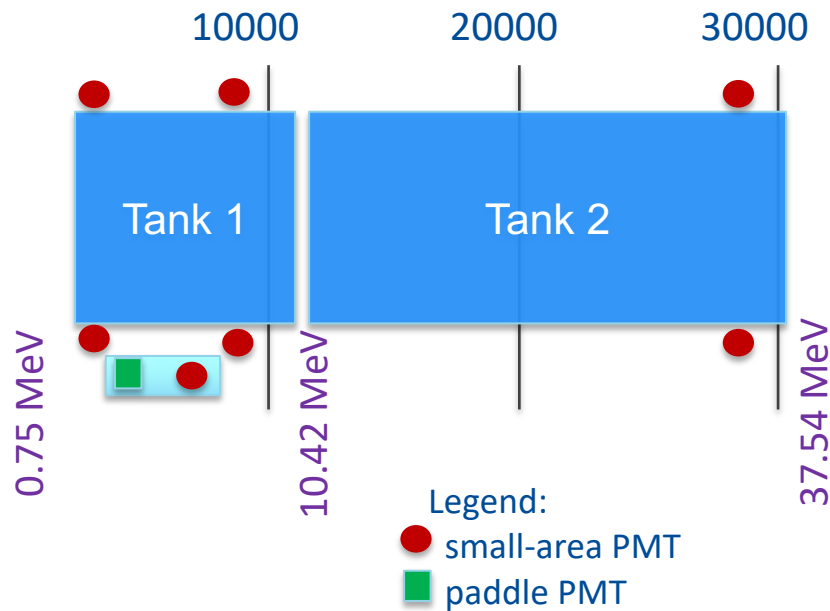   - However LM response not calibrated

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Instrumentation in Linac

- Progress in 2021
  - Reduced noise in BLM circuits
  - Calibrated SCL BLM response based on distance to beam pipe
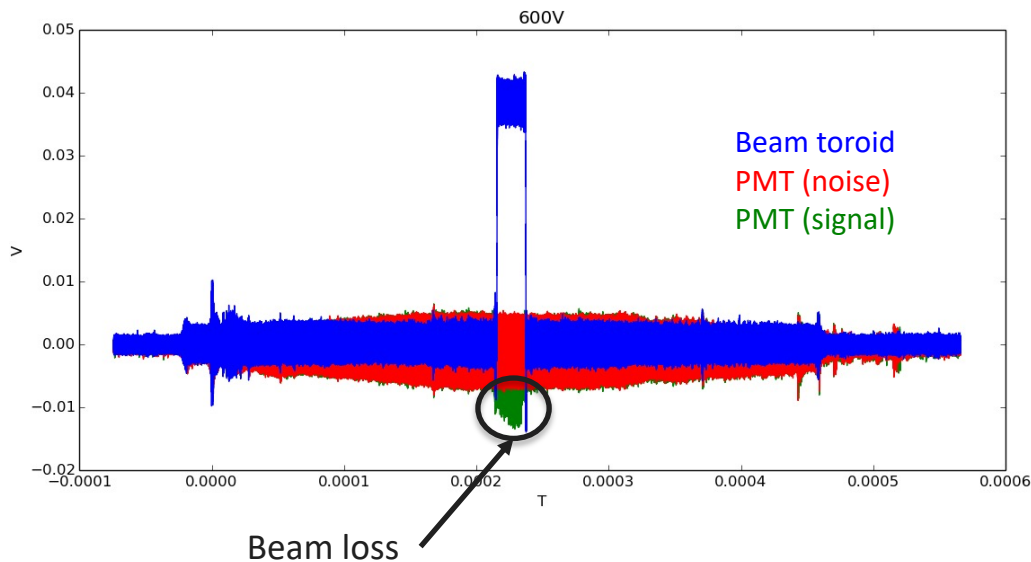
DTL BLM installation

- Progress in 2021
  - Installed 6 stationary and 2 movable* PMT-based BLMs

10000   20000   30000

Tank 1   Tank 2

0.75 MeV   10.42 MeV   37.54 MeV

Legend:
● small-area PMT
■ paddle PMT

*translation system being designed

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DTL BLM installation

- ## Progress in 2021
  - – Installed 6 stationary and 2 movable* PMT-based BLMs
  - – Observed losses at 750 keV!

600V

Beam toroid
PMT (noise)
PMT (signal)

Beam loss

*translation system being designed

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DTL BLM installation

- Progress in 2021
  - Recommissioned Bunch length detector in Transition section
  - Bunch length measurement: useful for matching DTL to SCL
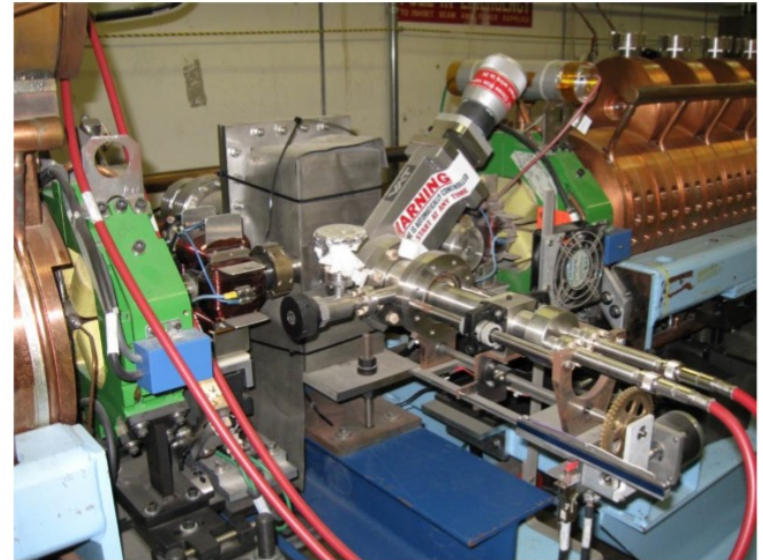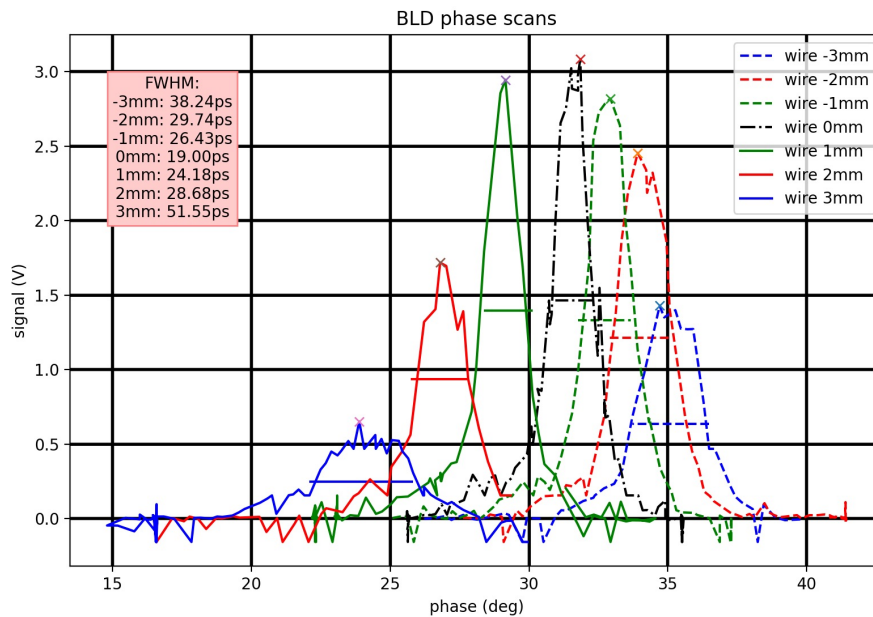
BLD phase scans

FWHM:
-3mm: 38.24ps
-2mm: 29.74ps
-1mm: 26.43ps
0mm: 19.00ps
1mm: 24.18ps
2mm: 28.68ps
3mm: 51.55ps

wire -3mm
wire -2mm
wire -1mm
wire 0mm
wire 1mm
wire 2mm
wire 3mm

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Instrumentation in Linac

- Status as of Jan 2021
  - DTL diagnostics limited by tank design
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  - Multiple BLM, TOR and BPM in SCL
    - However LM response not calibrated

- Progress in 2021
  - Installed PMT-based BLMs in DTL
  - Reduce noise in BLM circuits
  - Calibrated SCL BLM response based on distance to beam pipe
  - Recommissioned Bunch length detector in Transition section
  - Recommissioning Griffin ToF detector in 400 MeV section

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ML for longitudinal optimization
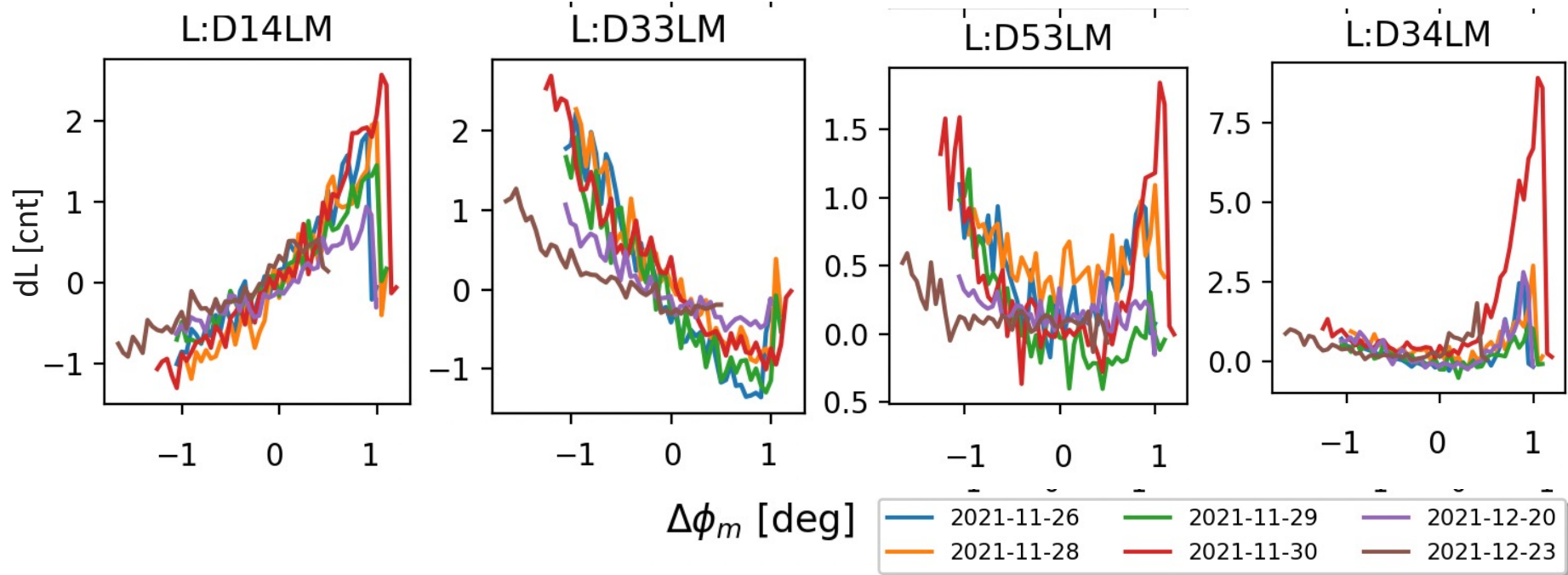
- Two main goals
  Focus today
  - Short-term: offline optimization of multi-RF systems
  - Longer-term: Real-time momentum control via FPGA-embedded system

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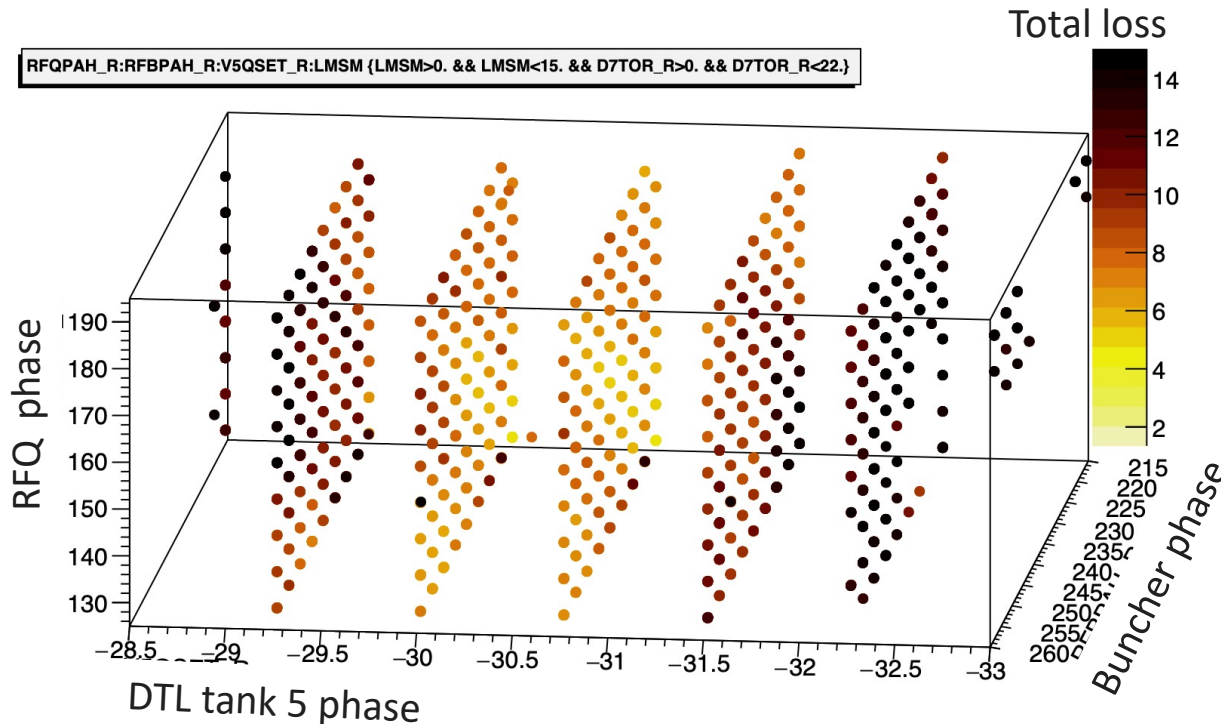
Offline optimization of multi-RF phases with ML

- Loss monitor, toroid and BPM patterns correlated with RF parameters
  - Correlations non-trivial in some cases

Select BLM readings vs. Tank 5 phase

Offline optimization of multi-RF phases with ML

- Loss monitor, toroid and BPM patterns are correlated with RF parameters

- We aim to train a model to recognize those correlations, and find optimal RF setting for daily operations

RFQPAH_R:RFBPAH_R:V5QSET_R:LMSM {LMSM>0. && LMSM<15. && D7TOR_R>0. && D7TOR_R<22.}

Total loss

3D pattern of total loss vs RFQ, Buncher and DTL tank 5 phase set points

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# Offline optimization of multi-RF phases with ML

- Status
  - Took multiple training data sets while varying three RF phases
  - Trained simple DNN model to reconstruct phase set points based on BLM and TOR data: proof of concept that relationships can be extracted
- Next steps: collaborate w/ PNNL to develop control network
  - Offline optimization of all RF parameters
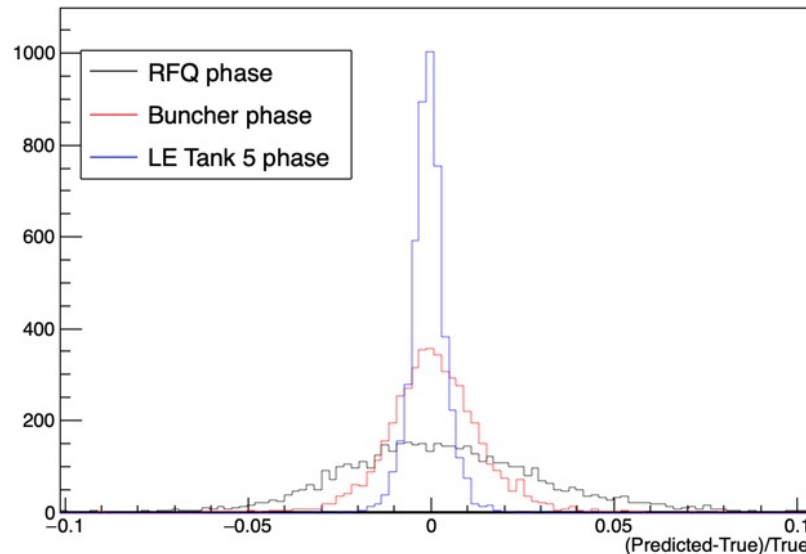
Simple model performance on test data (from summer 2021)

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Real-time momentum control of a single cavity

- Beam loading causes energy spread along the Linac pulse

- Beam momentum going into Booster regulated by adjusting phase of SCL module 7

- Goal: reduce long-term momentum drift as well as momentum deviation in pulse

  – Real-time regulation based on ToF and other diagnostics
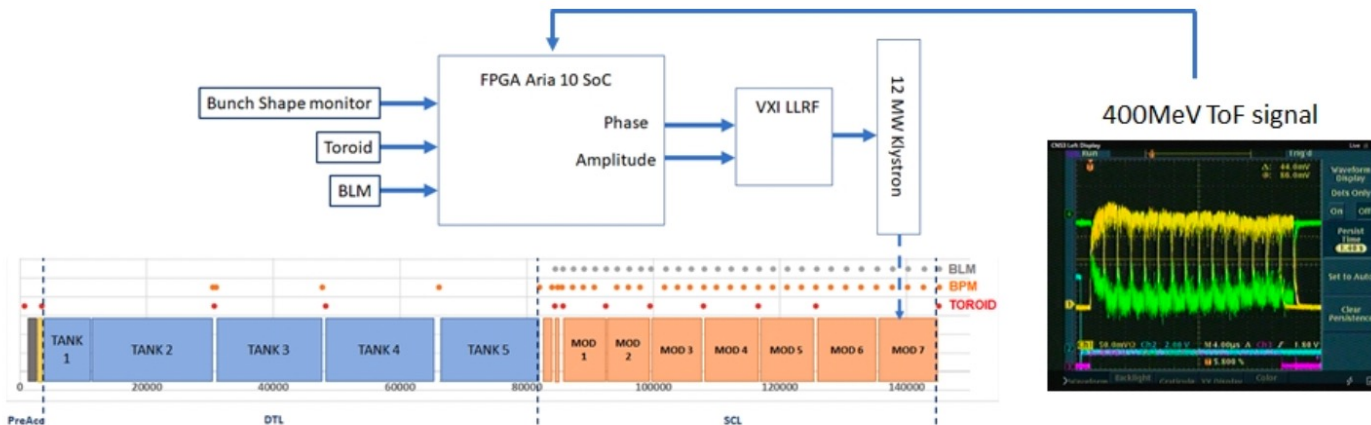
Summary

- Goal: deliver stable, high intensity beam to users
  - Daily tuning of RF parameters to reduce beam loss and increase beam output
- Challenges
  - Tuning relies on robust and stable diagnostics data
  - Correlation of diagnostics data & RF parameters not always trivial
  - Cannot manually tune many RF parameters simultaneously
- Our approach
  - Revisit instrumentation
  - Explore ML techniques for RF regulation
    - Offline optimization of multiple RF parameters
    - Real-time momentum control

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Backup slides

Presenter I Presentation Title   1/14/22

Transverse Focusing

- Quadrupole (Quad) Focusing
  - How to keep charged particles together?
  - Dipoles can only bend in one direction
  - Quads can squeeze or stretch
    - Can only focus in one plane

Vertical Focusing

Alternating gradients provides focusing in both planes. The repetition of vertical and horizontal focusing is referred to as the "lattice".

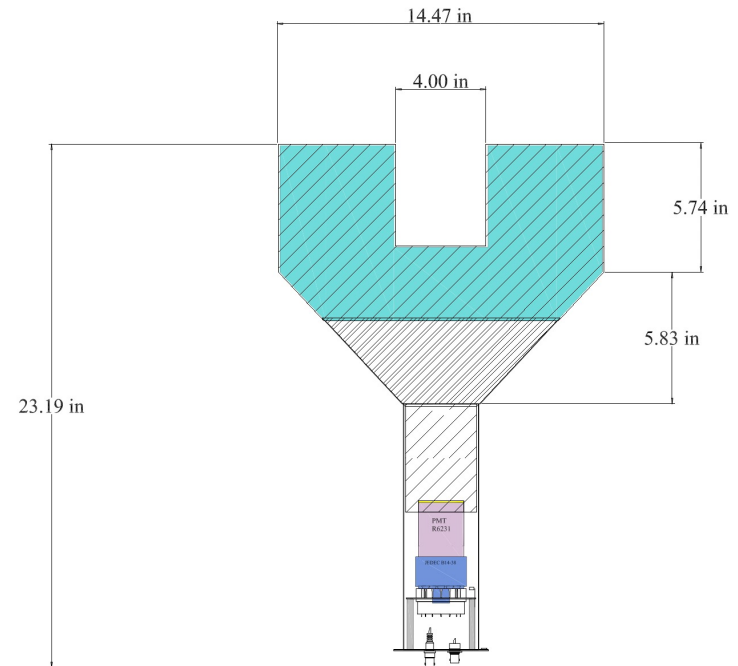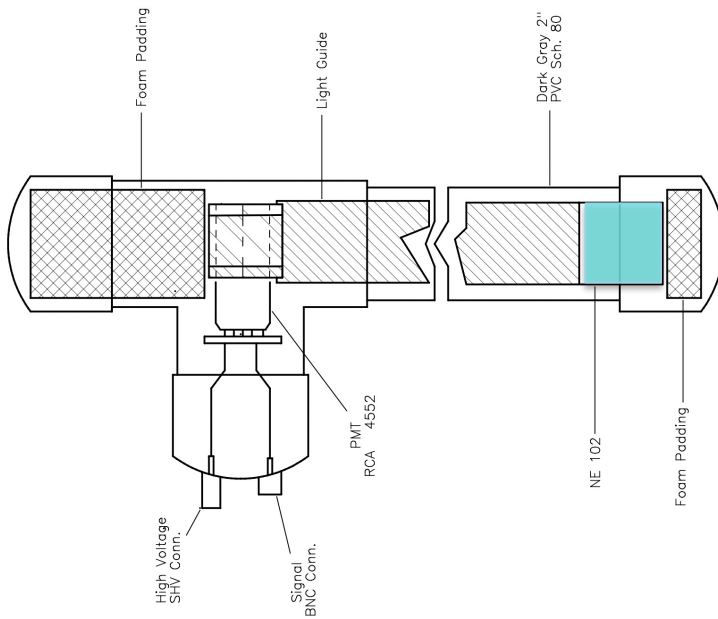The lattice defines how particles move in an accelerator.

Horizontal Focusing

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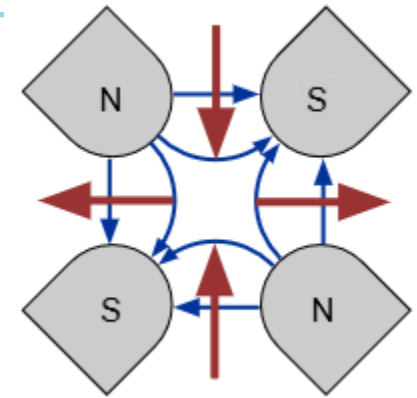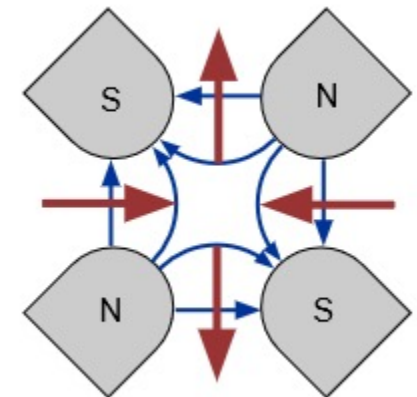
PMT-based BLMs

- Obtained/calibrated 7 small-scintillator-area PMT assemblies & 3 large-area paddles

Bunch length detector: basic idea

- Originally designed by A. Freschenko at INR

- Beam hitting wire produces e-
- e- mimic beam structure
- RF deflector: translates time structure into spatial
- Lens focuses e-
- RF cavity phase manipulation allows to scan full bunch

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